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Serrated flow in cast ZE43 alloy

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Plastic deformation of solid solutions is occasionally accompanied by plastic instabilities, i.e. serrated flow or the Partevin-Le Chatelier (PLC) effect. The PLC effect has been observed and investigated in various kinds of aluminum alloys [1–5]. For most aluminum alloys, this effect is observed at ambient temperature. The dynamic interaction between mobile dislocations and diffusing solute atoms, known as dynamic strain aging (DSA), is commonly accepted to account for the observed phenomena [6–11].

Compared to the extensive investigations on serrated flow of aluminum alloys, only a few papers have been concerned with the serrated flow in magnesium alloys. Couling [12] briefly reported the anomalous yielding effect in a Mg–0.5%Th alloy at testing temperatures from 373 K to 663 K. Chaturvedi et al. [13, 14] reported serrated flow in an Mg–10 wt.%Ag solid solution at temperatures between 326 K and 397 K. Zhu et al. [15] recently observed serrated flow in a 16-h-aged Mg–5Y–4Nd alloy and Corby et al. [16–19] found serrations in a AZ91 alloy when tested at room temperature. There seems no other reported work on serrated flow in magnesium alloys.

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The present paper reports our observations on serrated flow in a cast ZE43 alloy (Mg–4 wt.%Zn–3 wt.%RE, here RE refers to misch metal). Specimens prepared from the cast ZE43 alloy were annealed at 798 K for 10 h, and quenched from 798 k into hot water (353 K), then taken out to room temperature (T_4 treatment). In addition, Half of the hot-water quenched specimens were aged at 523 K for18 h (T_6 treatment). Tensile tests were conducted on a screw-driven Instron testing machine at various initial strain rates at temperatures ranging from room temperature to 573 K.

Serrations on the stress–strain curves of the specimens in both T_4 and T_6 conditions were observed in a temperature range from 393 K to 513 K. Outside this temperature range, smooth flow curves were obtained.

Figure 1 Shows segments of the flow curves of the specimens in both T_4 and T_6 conditions at a strain rate of $2.4 \times 10^{-5}\mathrm{s}^{-1}$ and a temperature of 473 K, where the serrations were most pronounced.

It can be seen that periodical serrations develop after about a 1% critical strain, ε_c. The serrations start to appear as a sequence of small yield points, and with increasing strain, the magnitude (stress drop) of the serrations becomes larger. The higher flow stress for the specimens in T_6 condition indicates a precipitation strengthening effect. The power law model $\sigma = k\varepsilon^n$ was used to fit the stress–strain curves, giving work hardening exponent n for the two heat treatment conditions a value of 0.31. The specimens in T_6 condition develop serrations later than that in T_4 condition, but the stress drops seem larger. The possible reason for the higher stress drops of the specimens in T_6 condition is due to the effect of

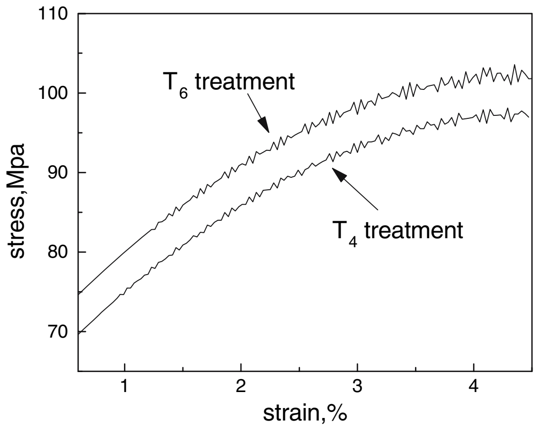

Fig. 1 Segments of flow curves of the specimens obtained at a strain rate of 2.4×10^{-5} s^{-1}at a temperature of 473 K

precipitates which hold up the movement of dislocations.

In contrast to many aluminum alloys in which precipitation has been reported to suppress the occurrence of serrated flow [2, 3], the present ZE43 alloy exhibits serrated flow even when tested in peak aged condition. This result is in accordance with the WE54 alloy which was solution treated at 798 K for 8 h and aged at 523 K for 16 h [15]. The reason for peak aged Mg alloys containing rare earth metals showing serrations is that the structure still contains a significant volume fraction of solute atoms [15]. The delay of the critical strain of the specimens in T_6 condition is due to the precipitation of solute atoms (Zn or RE) by aging, leading to a decreased concentration of the solute atoms in the Mg matrix.

The critical strain, ε_c, is a significant parameter of serrated flow, and strongly depends on strain rates, $\dot{\varepsilon}$, and testing temperatures. This dependence has been treated by various DSA models [6–10] and is generally expressed as $\varepsilon_c^{(m+\beta)} = K\dot{\varepsilon}\exp(Q/RT)$, where m and β are the respective strain exponent for vacancy concentration C_v and mobile dislocation density ρ_m during plastic deformation (in the relationship $C_v \propto \varepsilon^m$ and $\rho_m \propto \varepsilon^\beta$), K is a constant, Q the apparent activation energy, and R the gas constant. The variations of critical strain ε_c, as a function of strain rates is plotted in Fig. 2a. The data points follow a linear relationship, and gives (m +β) two values of 1.8 and 2.3,corresponding to T_4 and T_6 conditions, respectively. The value 1.8 is slightly higher than the 1.44 found for the Mg–10 wt.%Ag alloy [13, 14], but is lower than 2.2 for Mg–Y–Nd alloy [15]. The high value of (m +β) of 2.3 obtained for ZE43 alloy in T_6 condition is attributed to decreased concentrations of Zn and RE in the Mg matrix caused by aging.The difference of (m +β) values should imply different diffusive mechanisms for Zn and RE, which will be discussed further.

The variations of the critical strain, ε_c, as a function of temperatures at a strain rate of 2.4×10^{-5} s^{-1} is plotted in Fig. 2b. From the slopes of the plot and the values of (m + β), the apparent activation energies, Q, for the serrated flow are calculated to be 45 and 73 kJ/mol, respectively. The Q value of 45 kJ/mol is close to the 50 kJ/mol obtained in a Mg–10 wt.%Ag alloy [13, 14], and 73 kJ/mol is close to 75 kJ/mol obtained in a Mg–5 wt.%Y–4 wt.%Nd alloy [15] which has been aged for 16 h before testing.

Nevertheless, as the concentration of the solutes that are necessary to produce serrated flow always decreases with aging, the high stress drops of the specimens gained in T_6 condition cannot be understood without considering the influence of precipitates. Serrations result from the dynamic interaction of diffusive solute atoms with mobile dislocations temporarily arrested at obstacles [8–10]. Solute atoms diffuse to the mobile dislocations by a pipe diffusion mechanism

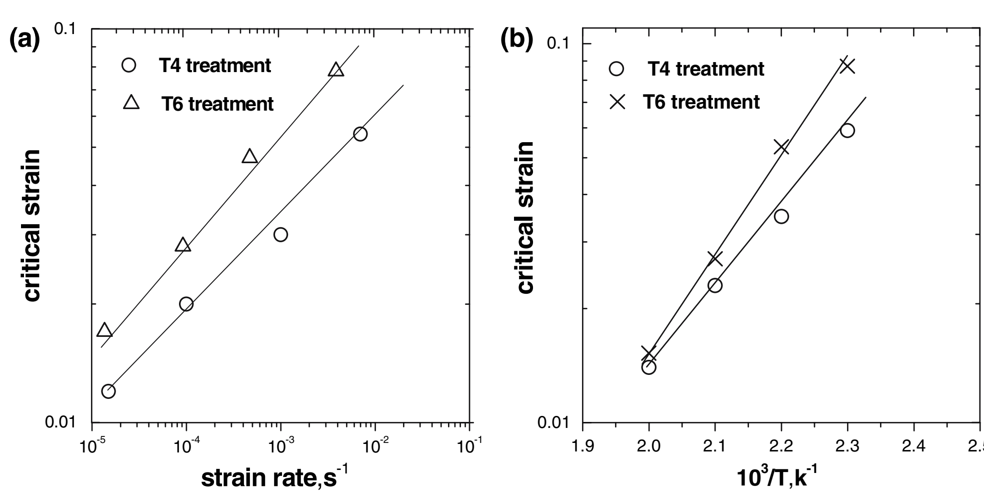

Fig. 2 The variations of the critical strain, ε_c, as a function of (a) strain rates at 443 K and (b) temperatures at a strain rate of 2.4×10^{-5} s^{-1}

along the forest dislocations [10, 11], thus the strain dependence of forest dislocation density accounts for the need for a critical strain for serrated flow to occur [8, 10]. Under this assumption, the forest dislocations are an important factor for the serrations to develop, as they serve as the obstacles for mobile dislocations and the paths along which the solute atoms diffuse to the mobile dislocations. However, besides forest dislocations or tangles of dislocations that are regarded as pinning sites of dislocations [2–4]. precipitates can also serve as additional obstacles for the movement of dislocations. The precipitates impede dislocation motion most effectively in peak aged condition, caused either by an increase in volume fraction, or by a favorable size or distribution of precipitates. The time during which dislocations are arrested by solutes is prolonged. Either a higher local solute concentration or a stronger pinning of dislocations can be induced, compared to without the influence of precipitates. Moreover, a local rearrangement of the structure of the precipitates in the stress field where mobile dislocations are piled up can be induced through shearing of dislocations, leading to local dissolution of precipitates [2]. The dissolution of precipitates sharply enhances the concentration of solute atoms near the piled-up dislocations, and the dissolved solutes immediately develop solute atmospheres, giving rise to the DSA process. Because this DSA process is induced by the dissolution of precipitates, it should be called secondary DSA.

The finding of serrated flow in the present ZE43 alloy is very important since the PLC effect leads to band-type macroscopic surface markings [4]. These limit the potential application of the materials when good surface quality is required, such as for automotive exterior panels. For this reason many studies of PLC effect have been given to aluminum alloys [5, 20–23]. It is apparent that equal concerns should be given to Magnesium alloys.

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